AN AUTOMATIC NETWORK ANALYZER SYSTEM

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INTRODUCTION

One of the most important trends in technology today is the rapid increase in sophistication of microwave equipment. Because of this trend, it is becoming absolutely necessary to completely and accurately characterize components and systems at microwave frequencies. This is extremely important in the systems area where many individual components are combined. In order to meet overall system requirements, each component in the system must be fully characterized so that its effect on the performance of the entire system is exactly predictable. While accurate characterization is the most important measurement feature demanded by modern microwave technology, it is by no means the only requirement. Future measurement systems must also have the capability to make precision measurements rapidly, display measured parameters in the most descriptive form, and require a minimum of special operator skill. These requirements must be met if critically-scarce technical personnel are to be relieved from time-consuming measurement routines for more challenging and creative efforts.

This article describes a new microwave measurement system which represents a significant contribution towards satisfying the severe requirements mentioned above. Five essential features of the new system demonstrate its capability to fully and economically characterize the linear response of microwave devices.

Complete Device Characterization

The device under test is measured in terms of its generalized scattering parameters or s-parameters. Advantages associated with s-parameter measurements are well-documented.[1-6] Fundamental to complete device characterization is that both the magnitude and phase portions of each s-parameter are measured. Even in those cases where the operator does not need phase information, this is essential for system calibration and therefore for accurate device characterization.

Standards Laboratory Accuracy

Measurements are made with an accuracy at least as great as those obtained from specialized standards laboratory procedures for point-to-point calibration. This means that the measurement system's residual, gain tracking, and source match errors are removed through the use of such fundamental standards as precision sliding loads, shorts, and line lengths. These standards are inherently stable and derived from easy to measure physical characteristics. Most important is the capability to perform highly accurate measurements in both coax and waveguide without necessitating any hardware changes as long as the appropriate reference standards are used. Provisions are also provided for automatically adjusting for the calibration curves of the reference standards.

Measurement Speed

The above precision measurements are achieved without going through the extremely lengthy calibration and measurement times previously necessary. As a rule of thumb, the new measurement system is between 50 and 150 times faster. For example, a precision measurement job previously requiring eight hours would only take between three to ten minutes. Most of this time is spent on the unavoidable job of physically connecting the reference standards and the device under test.

Broad Measurement Flexibility

Any characteristic of linear devices may be displayed without requiring expensive hardware changes. The data obtained from measuring the s-parameters of the device under test is first automatically corrected for system errors, and can then be transformed, compared, selected, or operated on in countless ways, either automatically or through simple instructions. Further, this information, whether it be the corrected s-parameters or some other device characteristic, is displayed in its most usable form without manual manipulation. The measurement system also has provisions for network synthesis on a real-time basis.

Minimum Operator Skill Required

A minimum amount of technical skill or knowledge is required to operate the system so that precision measurements are consistently achieved on a routine basis. Either the operator uses simple English commands, or he follows a programmed text of instructions on a step-by-step basis. Thus, measurements can be made in a previously specified manner and sequence. In addition, complicated measurement procedures developed by microwave experts are used without requiring detailed knowledge on the part of the operator. This is particularly relevant to the sophisticated calibration procedures. All important system functions are under automatic control which greatly reduces operator errors (such as incorrectly setting instrument controls and erroneously reading output displays).

SYSTEM DESCRIPTION

A simplified block diagram of the new microwave measurement system, called the Automatic Network Analyzer, is shown in Fig. 1. The system has three major sections: the Signal Source, the Network Analyzer, and the Computer. By considering the function of each of these sections separately, the operation of the entire system can be easily understood.

The Signal Source section consists of a sweep oscillator controlling a multiple set of RF signal sources and a signal multiplexer. This particular signal source has a multi-octave bandwidth (0.1-12.4 GHz), but other sources are also available which cover only single octave bands. The sweep oscillator is modified and interfaced to the computer to allow for digital programming of the RF frequency. RF switching is accomplished by the signal multiplexer which connects the oscillator outputs to the main signal line into the Network Analyzer section. This switching is also under computer control. Automatic level control (ALC) is used to insure a reasonably level input signal to the device under test.

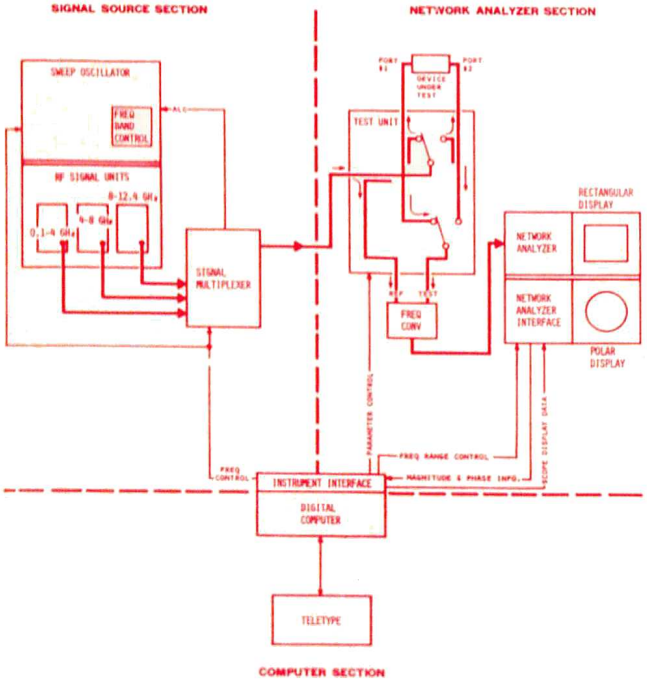

Fig. 1 — Automatic Network Analyzer System.

The Network Analyzer section measures the s-parameters of the device being characterized. A two-port test unit is shown in Fig. 1. Other test units are also available for measuring up to four port devices — two ports at a time. Any one of the four s-parameters representing a two-port device can be measured by switching the RF signals inside the test unit. This switching is computer-controlled. The network analyzer portion of the sub-system is simply a microwave frequency vector ratio voltmeter which measures the amplitude ratio anad phase difference between the reference and test channels.[7,8] Thus, for the position of the test unit switches shown in Fig. 1, the port 1 reflection characteristics of the device under test would be measured. To measure over a wide dynamic range, a precision IF substitution method is employed in the network analyzer. The network analyzer interface automatically programs the test channel IF gain to insure optimum signal to noise ratios. (This IF gain setting is transferred to the computer after each measurement.) Two integrating analog to digital converters in the network analyzer interface are used to accurately digitize the magnitude and phase information for computer input. Several other of the network analyzer's functions under computer control are the frequency range and phase-lock status. The network analyzer interface routes oscilloscope information from the computer — corrected reflection data to the polar display and corrected transmission data to the rectangular display.

The Computer section consists mainly of a small instrumentation computer.[9] As is clear by now, all important functions of the microwave instruments can be controlled by the computer. Equally significant is the fact that the computer can be used to store the system's own frequency-dependent vector errors (both amplitude and phase) as well as perform mathematical calculations. These features are absolutely vital to the very important calibration procedure about to be discussed.

The system has two operation modes: automatic or computer-control and manual-sweep. Computer-control of the system is conceptually straight forward. First the computer sets the sweep oscillator and network analyzer to the required frequency and then routes the RF signal through the multiplexer to the test unit. Next, the s-parameter to be measured is selected and the resulting amplitude and phase information digitized and transferred to the computer. Finally, the raw measurement data is corrected for system errors (previously measured) and then transformed into the desired parameters for display on either an oscilloscope or the teletype. Manual-sweep operation of the system is obtained by simply pushing one button which removes all of the microwave instruments from computer control. This is very important since it gives the operator an instant swept frequency display of the status of the measurement system. Thus, the operator assures himself that the device under test is correctly inserted and that the connectors are tight.

CALIBRATION PROCEDURE

All measurement systems introduce errors into the measurement results. For precision measurements, those errors which are predictable must be greatly reduced by either designing a system very close to ideal or else by using the system to measure its response to reference standards substituted for the device under test.* At microwave

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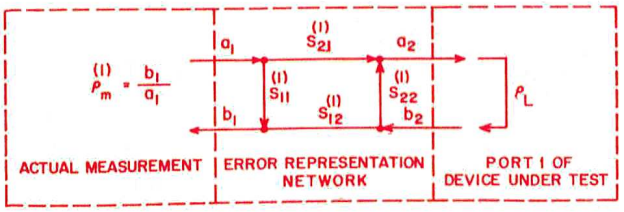
* *Random errors can only be reduced through careful system design and by time-averaging the measurements.*

frequencies, the former approach has usually proven to be impracticable. This is because the high-frequency signals must be measured using such devices as directional couplers, magic tees, attenuators, detectors, and other components which cannot be designed with anything like ideal properties. The end result is an intolerable level of measurement inaccuracy caused mainly by the ever-present microwave measurement problems of which directivity, coupling variation, and mismatch errors are common examples. To achieve standards laboratory accuracy, it is almost always necessary to calibrate the system with respect to reference standards at each frequency — usually by physically adjusting tuners and various offset controls in the system. While measurement accuracy will be greatly improved, the process is tedious and costly. However, system errors can be removed in an equivalent manner without physically "tuning" them out. Using a high resolution digital readout, the errors are measured for each of the reference standards. After the device under test is measured, the results are adjusted by solving a set of complex network equations. There are some advantages in correcting for errors numerically instead of physically. First, the error reduction is only limited by the resolution of the system if enough significant digits are used. Second, the calibration and measurement correction process can be carried out at fast data acquisition speeds with no manual control adjustments required. Finally, very little extra effort is required to use a sufficient number of reference standards to fully characterize the system's errors — something which is not always done even in standards laboratories. The numerical correction approach is employed in the Automatic Network Analyzer. To see just how comprehensive the calibration capability of the automatic system is, the procedure for removing errors in the two-port measurement system shown in Fig. 1 will be outlined.

The calibration procedure can be separated into three parts: (1) individual port error measurements, (2) combined port error measurements, and (3) correction of actual measurements.

Individual Port Error Measurements

Errors at each port are represented by a general two-port s-parameter network.* For example, port 1 would be characterized by:



Some of the better known, but *not* all, of the port 1 errors represented by the s-parameters are (see Network Analyzer Section of Fig. 1):

$S_{11}^{(1)}$ = Residual Errors = Directivity errors of couplers. Test to reference channel isolation.

$S_{21}^{(1)}\ S_{12}^{(1)}$ = Gain Tracking Errors = Tracking variation of reference and test channels of frequency converter. Tracking variations of coupler coefficients.

$S_{22}^{(1)}$ = Source Match Errors = Mismatch at connector.* Internal mismatches down main line of directional coupler.

Using the nontouching loop rule [Reference (10), pages 118-122]:

$$\rho_m^{(1)} = S_{11}^{(1)} + \frac{S_{21}^{(1)}\ S_{12}^{(1)}\ \rho_L}{1 - S_{22}^{(1)}\ \rho_L}$$

Thus, the true value of ρ_L is unknown since the s-parameters are unknown. To overcome this problem, port 1 of the measurement system is calibrated by measuring reference standards with accurately known ρ_L's and solving for the s-parameters in the error representation network. A precision sliding load termination determines $S_{11}^{(1)}$.

If $\rho_L = |\rho_L|\ \angle\phi$ then,

$$\rho_m^{(1)} = S_{11}^{(1)} + S_{21}^{(1)}\ S_{12}^{(1)}\ (|\rho_L|\ \angle\phi).$$

(Note: For precision sliding loads and values of $|S_{22}|$ found in practice, it is true that $|S_{22}|\ |\rho_L| << 1$).

Therefore $S_{11}^{(1)}$ is the center of a circle with radius $|S_{21}^{(1)}|\ |S_{12}^{(1)}|\ |\rho_L|$ and is easily determined by the computer from stored measurement data for different values of ϕ.

The $S_{21}^{(1)}$ $S_{12}^{(1)}$ and $S_{22}^{(1)}$ error parameters must be solved simultaneously. First, a precision short ($\rho_L = -1$) is measured and then a precision short at the end of a precision length of transmission line ($\rho_L = 1\ \angle\sigma$) is measured. Since there are two equations with two unknowns, the unknown $S_{21}^{(1)}$ $S_{12}^{(1)}$ and $S_{22}^{(1)}$ parameters can be calculated:

$$\rho_{m_1}^{(1)} = S_{11}^{(1)} - \frac{S_{21}^{(1)}\ S_{12}^{(1)}}{1 + S_{22}^{(1)}}$$

$$\rho_{m_2}^{(1)} = S_{11}^{(1)} + \frac{S_{21}^{(1)}\ S_{12}^{(1)}\ (1\ \angle\sigma)}{1 - S_{22}^{(1)}\ \ (1\ \angle\sigma)}$$

* *It should be noted that all s-parameters have both a magnitude and phase component.*

* *This error is removed to within the connector repeatability.*

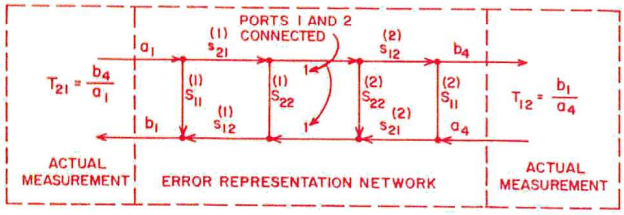
Repeating the above procedure for port 2 gives six calibration constants which fully characterize each measurement port separately:

$$C_1^{(1)} = S_{11}^{(2)},\ C_2^{(1)} = S_{21}^{(1)}\ S_{12}^{(1)},\ C_3^{(1)} = S_{22}^{(1)},$$

$$C_1^{(2)} = S_{11}^{(2)},\ C_2^{(2)} = S_{21}^{(2)}\ S_{12}^{(2)},\ C_3^{(2)} = S_{22}^{(2)}.$$

Combined Port Error Measurements

Both ports must be connected together in order to characterize the transmission errors through the two ports of the test unit (see Fig. 1). This time the error representation network looks like:



By inspection, the transmission characteristics of the network are:

$$T_{21} = \frac{S_{21}^{(1)}\ S_{12}^{(2)}}{1 - S_{22}^{(1)}\ S_{22}^{(2)}} \qquad T_{12} = \frac{S_{21}^{(2)}\ S_{12}^{(1)}}{1 - S_{22}^{(1)}\ S_{22}^{(2)}}$$

$$T_{21} = \frac{S_{21}^{(1)}\ S_{12}^{(2)}}{1 - C_3^{(1)}\ C_3^{(2)}} \qquad T_{12} = \frac{S_{21}^{(2)}\ S_{12}^{(1)}}{1 - C_3^{(1)}\ C_3^{(2)}}$$

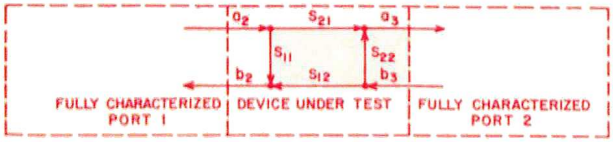
Because of physical considerations, the S_{21} and S_{12} parameters are not the same as the ones in the individual port calibration models. This presents no problem since the terms always appear in a product form and therefore new calibration constants can be defined:

$$C_4^{(1)} = S_{21}^{(1)}\ S_{12}^{(2)},\ C_4^{(2)} = S_{21}^{(2)}\ S_{12}^{(1)}.$$

Thus, the calibration of the two-port Automatic Network Analyzer involves determining the values (both magnitude and phase) of eight calibration constants at each measurement frequency.

Correction of Actual Measurements

The linear response of any two-port device is represented by a general s-parameter network placed between measurements ports 1 and 2:



Using the non-touching loop rule and substituting in the calibration constants gives the following four equations in a form suitable for solving with iterative techniques:

$$S_{12} = \frac{(D)\,(T_{12})}{C_4^{(2)}},\quad S_{21} = \frac{(D)\,(T_{21})}{C_4^{(1)}},$$

$$S_{11} = \frac{(\rho_m - C_1^{(1)})\ (D) - C_2^{(1)}\ C_3^{(2)}\ S_{12}\ S_{21}}{C_2^{(1)}\ (1 - C_3^{(2)}\ S_{22})},$$

$$S_{22} = \frac{(\rho_m - C_1^{(2)})\ (D) - C_2^{(2)}\ C_3^{(1)}\ S_{12}\ S_{21}}{C_2^{(2)}\ (1 - C_3^{(1)}\ S_{11})}.$$

Where:

$$D = (1 - C_3^{(1)}\ S_{11})\ (1 - C_3^{(2)}\ S_{22}) - C_3^{(1)}\ C_3^{(2)}\ S_{11}\ S_{22}$$

The iterative approach starts by assuming that D equals one. Next the four calibration equations are solved to obtain values for the unknown s-parameters. Using S_{11} and S_{22} a new value is found for D. This process is repeated until the successive differences in D are negligible. By using a computer, all four s-parameters of the device under test are determined in less than a second.

While the calibration procedure is very sophisticated, the instructions to the operator are extremely simple with the computer asking questions and giving commands on a step-by-step basis. This is illustrated in Fig. 2 where the operator's replies are underlined. A space is used to signify that an operation has been completed and the automatic system is to proceed to the next task.

```
? CALIB

CALIB FREQS IN MHz
START FREQ? 4000
STOP FREQ? 12000
STEP SIZE? 1000

CONNECT TERMINATIONS ON BOTH PORTS _____

SLIDING LOAD? YES
SLIDE LOAD _____
SLIDE LOAD _____
SLIDE LOAD _____

CONNECT SHORTS ON BOTH PORTS _____

WAVEGUIDE? NO
CONNECT OFFSET SHORT NO. 3 ON BOTH PORTS _____

CONNECT PORTS TOGETHER _____

CALIB PROCEDURE FINISHED

?
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Fig. 2 — Printout of calibration procedure.

MEASUREMENT EXAMPLES

The measurement examples shown are used to illustrate the types of measurements which can be made, the accuracies which can be achieved, and the types of display and readout which are provided. They are representative only and by no means is the Automatic Network Analyzer limited to just these measurements.

Fig. 3 shows the system's capability to accurately repeat measurements. In the first case, the 50-ohm coax termination used to calibrate the system was re-measured. Notice the excellent results, indicating accuracies limited largely by the effects of connector repeatability. Next, the two measurement ports were connected together and the system re-measured its calibrated transmission characteristics. Again excellent results are obtained with the main limitation being connector repeatability. These measurements serve to demonstrate the extremely accurate transfer characteristics of the Automatic Network Analyzer system. In other words, the system can be used as a microwave transfer standard between actual device measurements and the three reference standards mentioned in the calibration procedure.

The next example compares measurements made by Hewlett-Packard, Palo Alto, Microwave Standards Laboratory to those made on the Automatic Network Analyzer. An X-band waveguide 20% standard reflection was used as the device under test. It is significant to note that a coax to X-band waveguide adapter is required to make this measurement on the system. Fig. 4 indicates that the two absolute measurements agree to within a reflection coefficient error of about ±0.2%. This includes errors caused by using two different sets of reference standards to calibrate each measurement setup. Particularly noteworthy is the fact that a precision comparison was achieved even though the automatic system used an adapter with a ten percent reflection coefficient.

The measurement accuracy of the Automatic Network Analyzer system was maintained by calibrating with respect to the *waveguide* port of the adapter and thus removing not only system errors, but adapter errors as well. The standards lab expended ten hours to make these measurements whereas the total calibration and measurement time on the automatic system was less than ten minutes.

? VSWR

Freq (MHz)	VSWR	Return Loss (dB)
4000	1.000	76.8
5000	1.000	77.1
6000	1.001	70.9
7000	1.000	79.3
8000	1.000	81.5
9000	1.000	79.7
10000	1.001	70.9
11000	1.001	69.8
12000	1.000	77.0

? S21

Freq (MHz)	Mag (dB)	Angle (deg)
4000	.00	.0
5000	.01	.1
6000	.00	.1
7000	—.01	.0
8000	.01	—.0
9000	.00	—.1
10000	—.00	.0
11000	.02	.1
12000	.01	.0

Fig. 3 — Repeatability of Automatic Network Analyzer.

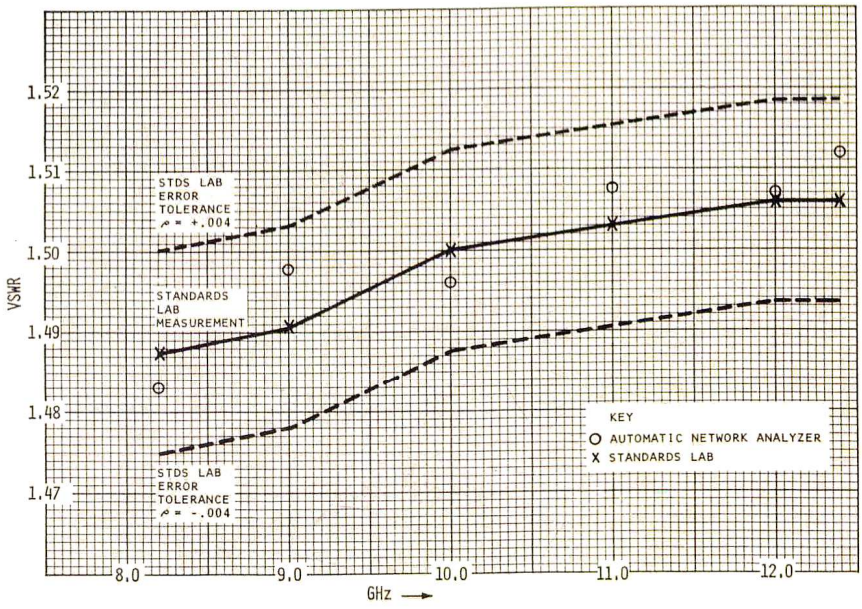
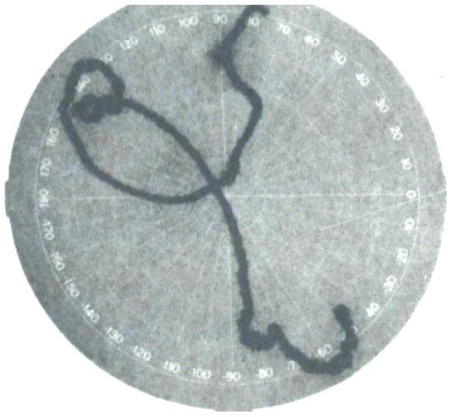


Fig. 4 — Measurement comparison between Automatic Network Analyzer and HP Palo Alto Microwave Standards Lab using X-band waveguide 20% reflection standard.

Fig. 5 illustrates measurement of a low VSWR 50 ohm coax termination. The upper photograph was taken with the system operating manually and shows the effect of residual system errors. The lower photograph shows the same measurement made under computer control with system errors calibrated out. Since the reflection magnitude scale of the oscilloscope display is automatically adjusted for the most meaningful range, it is necessary to show the full scale value ($\rho = 0.05$). Fig. 6 illustrates measurement of a high VSWR device, in this example, an offset short.* The important sources of error are source match and gain tracking. The lower photograph shows the arch of the perfect circle obtained when these errors are removed. In both examples, the corrected measurement data (reflection coefficient, VSWR, return loss, etc.) may also be obtained in printed copy form from the teletype.

Fig. 7 is illustrative of several transmission parameters which can be obtained. The photographs show the results of measurements on a 6 to 8 GHz bandpass coax filter over a range of 4 to 8 GHz. Test channel gain for these measurements is automatically ranged by the computer to obtain optimum signal to noise ratio. Again data is automatically scaled to obtain a full screen display. The vertical sensitivity (units/cm) used for each measurement



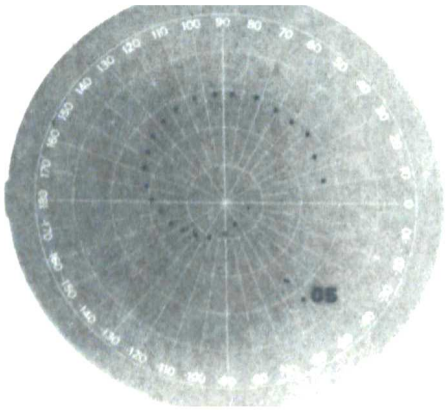
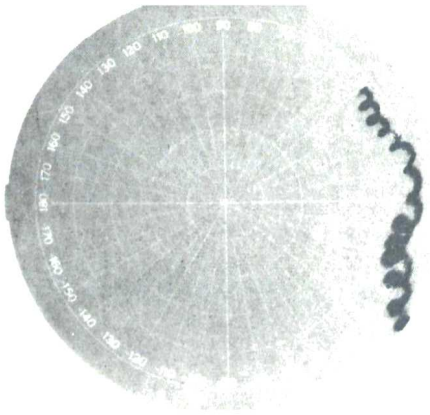


Fig. 5 — Reflection measurement of coax termination.
(a) Before system errors are removed
ρ = 0.05 full scale 8-12.4 GHz.
(b) After system errors are removed
ρ = 0.05 full scale 8-12.4 GHz.



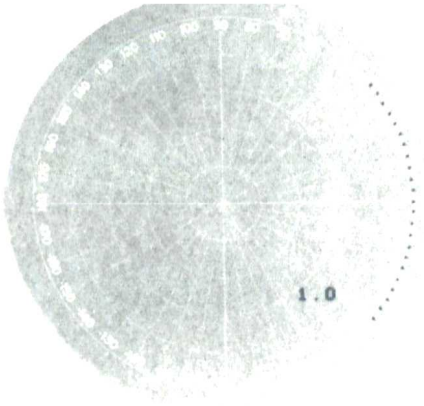
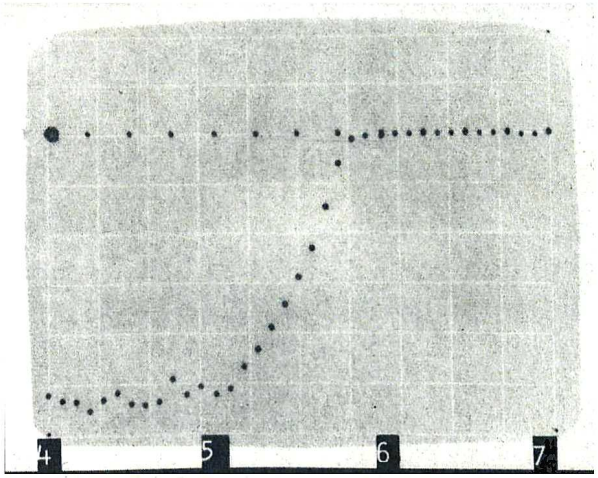


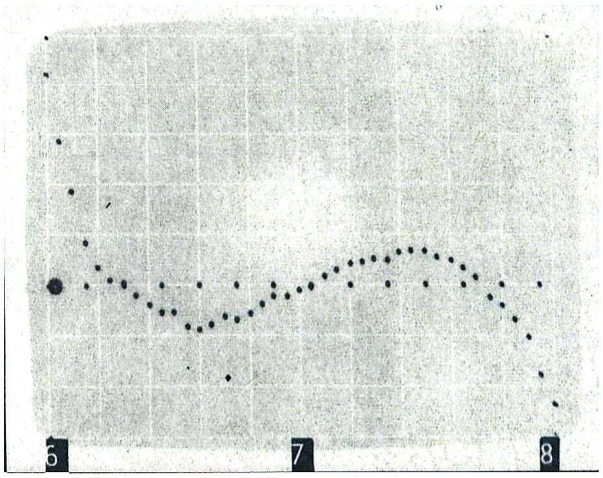
Fig. 6 — Reflection measurement of coax short.
(a) Before system errors are removed
ρ = 1.00 full scale 8-12.4 GHz.
(b) After system errors are removed
ρ = 1.00 full scale 8-12.4 GHz.

* *A short separated from the measurement reference plane by a precision air line.*

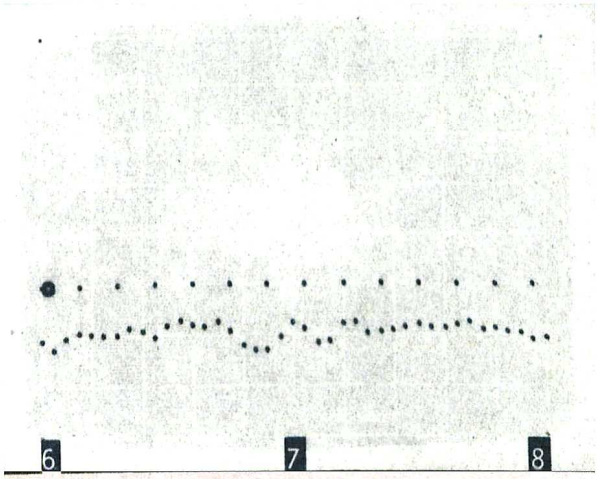
is printed out on the teletype along with the 3rd level being indicated on the oscilloscope display by a zero and a series of horizontal dots. Thus, a completely calibrated, full-scale display is always obtained with no adjustments or calculations on the part of the operator. Fig. 7 also demonstrates the powerful capability of the system to transform the corrected s-parameter measurements into other network parameters. The first photograph shows the corrected magnitude of the filter's forward transfer characteristics $|s_{21}|$ in the lower skirt and passband regions. This measurement covers a 100 dB dynamic range. The second photograph shows the details of insertion loss variations over the passband. By using a linear regression routine in the computer, the linear phase shift from 6-8 GHz is accurately removed so that smaller phase nonlinearities can be studied (third photograph). Finally, the very important parameter of group delay is calculated from the total phase shift curve and displayed in the fourth photo-



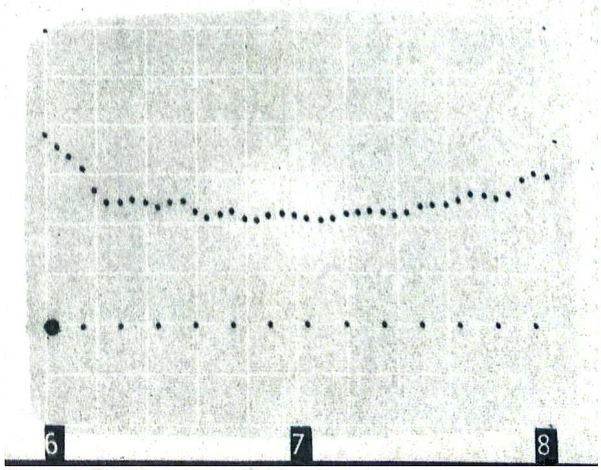
7-1 SKIRT ATTENUATION (4-7 GHZ)
20 DB/CM



7-3 NONLINEAR PHASE DEVIATION
(6-8 GHZ) 20°/CM



7-2 PASSBAND INSERTION LOSS
(6-8 GHZ) 1 DB/CM



7-4 GROUP DELAY (6-8 GHZ)
1 NANOSEC/CM

Fig. 7 — Transmission measurements of 6-8 GHz bandpass filters.

graph. Note that the filter has an *absolute* group delay of between two to four nanoseconds for signals within the passband (6 to 8 GHz) and variations are resolved to one-tenth of a nanosecond. To obtain the information in Fig. 7, the operator merely typed in the parameter names with the entire measurement and display sequence requiring less than two minutes. Again, the data displayed on the oscilloscope may also be printed out on the teletype if more resolution is desired.

Anyone who has made accurate measurements at microwave frequencies recognizes the unusual care which must be exercised in order to avoid introducing subtle measurement errors. For this reason, the above measurement examples are particularly significant because they not only show that a broad range of device characteristics were measured accurately but also that no special knowledge was required of the operator. Fundamental to achieving these results is that a new system calibration procedure, representing a departure from the usual approach, is used. Previously, special skill and care was necessary to *physically* reduce measurement errors by manually adjusting the system's response. This approach is time-consuming, tedious, and adjustment limited in its error correcting capability. The Automatic Network Analyzer system simply leaves the errors in the system *but* measures and remembers them. Thus, the new measurement system is essentially a high-resolution, automatic comparator. It was recognized earlier in the design of the system that to try to achieve automatic operation by only connecting a digital computer to an instrument meter output would give unsatisfactory results. Therefore, careful attention was directed towards integrating the computer and microwave instruments together into one fully automatic measurement system.

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